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Ocean Battlespace Sensing (OBS) S&T Department Annual Report
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Differential Frequency Hopping (DFH) Modulation for Mobile Underwater Sensor Networks

PI: Luca Cazzanti, Ph. D.
University of Washington
Applied Physics Laboratory
Seattle, WA 98105
phone: (206) 543-1374 fax: (206) 543-6785 email: luca@apl.washington.edu

Arindam Das, Ph. D.
University of Washington
Applied Physics Laboratory
Seattle, WA 98105
phone: (206) 543-9891 fax: (206) 543-6785 email: arindam@apl.washington.edu

LONG-TERM GOALS

The long-term goal of this research effort is to develop underwater acoustic communications algorithms based on differential frequency hopping (DFH) modulation that enable networked operations (i.e. multiple simultaneous users), as well as providing low probability of detection and intercept (LPD/LPI) and anti-jamming (AJ) capabilities.

OBJECTIVES

The specific objective of this effort is to adapt existing DFH algorithms developed for terrestrial communications for use in the doubly spread underwater acoustic channel. Key research goals are: (a) development of synchronization and demodulation schemes that are robust to various aspects of the environment using the DFH signal itself, and (b) development of equalization algorithms that exploit available spatial diversity for improving the bit error rate (BER). Variations in water depth, bottom type, sound speed profile, and source/receiver location can provide for wide ranges of multipath interference (resulting in time spread). Different wind and surface wave conditions in combination with platform motion can result in varying degrees of Doppler shift and spreading. The developed algorithms must work well across the range of conditions that might be encountered in real-life scenarios.

APPROACH

This project involves a close collaboration between Dr. Luca Cazzanti at APL/UW and Dr. Geoff Edelson at BAE Systems. Dr. Edelson has been involved in the development of the DFH algorithm

(Mills and Edelson, 2001), and has also been involved in a variety of other acoustic communications related projects for the Navy (Nagle et al., 2000). Dr. Cazzanti has experience in signal processing, adaptive equalization for digital communications, sonar, and underwater acoustics. Dr. Cazzanti also has experience with the Sonar Simulation Toolkit (SST).

A key part of this effort is the use of SST (Goddard, 2008) to simulate the propagation of communication sequences through the underwater acoustic environment. SST allows a user to specify an ocean environment with a wide variety of parameters relevant to acoustic signal propagation and reception: sound speed profile, bathymetry, surface and bottom characteristics, ambient noise levels, etc. The user can also specify locations and trajectories of acoustic sources and receivers within that environment, and signals to be transmitted by the sources. SST then uses acoustic propagation models and time series simulation techniques to produce properly calibrated digital time series of the signals that would be "heard" by the receivers. These time series can then be operated on by signal processing algorithms, ideally the same algorithms that would operate on acoustic data measured at sea.

APL-UW provides the results of the SST simulation studies to BAE Systems, thus enabling algorithmic improvements by BAE to the DFH modulation schemes. The team has collaborated on the processing of the simulated signal, assessment of the algorithms' performance, and design of enhancements to improve performance for use in the underwater channel, with special regard to the effects of Doppler.

Another key part of this effort is the analysis of DFH data collected during at-sea experiments. The measured data serves as a validation tool for our simulation environment and enables a better understanding and thus more accurate modeling of the underwater environments of interest for DFH-based acoustic communications.

WORK COMPLETED

The current effort builds on a previous three-year grant that focused on the effects of multipath and multiuser interference on DFH waveforms. Here we summarize that work, then discuss the current effort.

Summary of Work Completed During the Previous Grant
In the previous grant, we investigated the performance of DFH in the underwater acoustic channel, in both SST-simulated environments and in sea-trial scenarios. We also showed that blind equalizers can work well with and are easily incorporated into the DFH receiver algorithm. First, we simulated several underwater ACOMMS scenarios using SST. The modeled scenarios included both soft- and hard-bottom environments to explore the effects of the ocean bottom on the multipath. We also simulated single- and multi-user scenarios. Then, we demodulated the SST-simulated received signals with a baseline DFH receiver and computed the BER to quantify the performance. Based on an analysis of these results, BAE Systems designed improvements to the baseline DFH receiver to mitigate multiple access interference (MAI). The improved DFH algorithm was then tested on data collected from the RACE08 sea trial and yielded very good multi-user performance.

We also investigated the applicability of blind equalizers to the DFH receivers to SST-simulated DFH signals. The results showed that the constant modulus algorithm (CMA) for blind equalization works well to mitigate intersymbol interference (ISI) in the received DFH signal. The important result was that off-the-shelf equalization strategies can be incorporated in the DFH receiver easily.

Finally, we characterized the environment of the RACE08 experiment in terms of SST model parameters, so that proof-of-concept simulations can be run before future experiments in similar environments.

Work Completed During the Previous Year of the Current Grant
During the period March 2010-September 2010 we studied DFH in Doppler environments and related the DFH signal parameters and performance to the characteristics of the environment. We studied the relationship between Doppler-inducing environmental conditions, DFH performance, and DFH signal parameters. We linked the characteristics of the DFH received waveforms to standard accepted physics-based models of the interaction of sound with the water surface. We designed SST scenarios for studying platform motion-induced Doppler effects on the DFH signals. These simulations allowed us to perform a root-cause analysis of the errors in the received DFH sequences. We identified the need for iterative synchronization in the DFH receiver based on the root-cause analysis. We implemented a preliminary iterative synchronizer and measured its performance in terms of BER.

Work Completed During FY11
During the period October 2010-May 2011, we put together improved DFH processing from BAE systems, which resulted from last year's work, and SST simulations that modeled very difficult Doppler and multi path environments, comprising the surface and bottom effects we had studied, low SNRs. We characterized the performance of DFH under these conditions, for single- and multi-user scenarios, and for single-hydrophone and array processing. The results show that DFH is natively robust to strong ISI and Doppler effects even at very low SNRs for the single-user scenarios. The inherent robustness can be enhanced with simple phone-averaging array processing. For the multi-user case, more sophisticated Doppler tracking is needed. We published our findings in the Journal of Underwater Acoustics, and presented our research at the ASA meeting in Seattle.

RESULTS

We adopted the same scenarios as last year for the SST simulations. Figure 1 shows the experimental setup we used for the SST. We used a total of 8 users, 6 of which were moving away from the receiver array (at $1, 2, \ldots 6$ kts.) and the other 2 moving toward the reciever array at 2 and 3 kts. The receiver array consisted of 6 hydrophones, spaced 12 cm. apart. Wind speed was set to 3.5 m/s.

We computed the BERs using a new version of the DFH decoder that incorporates automatic delay tracking that overcomes the issue of synchronization slippage we had highlighted last year. As a first test of the improved delay-tracking DFH receiver, we simulated the transmission of the DFH waveforms in an ISI-free environment (we turned off the eigenray bottom reflections in SST). Figure 2 shows the results for such a case. The received waveforms are processed individually, that is there is no array processing involved. The BERs from each single-hydrophone reception are averaged to obtain the overall performance number. Note that DFH is natively robust to this environment for significant platform motion, even for very low SNRs. In fact, BERs of 10^{-4} are effectively zero-error transmissions.

We want to assess the performance of DFH when both platform motion and ISI are present. Figure 3 shows the results for the case of a very reflective bottom, which causes considerable ISI. Compared to the precious case, we notice that the transmissions are not error-free any more. It is possible to decrease the BER by combining the receptions, that is by applying array processing. In fact, even a very simple
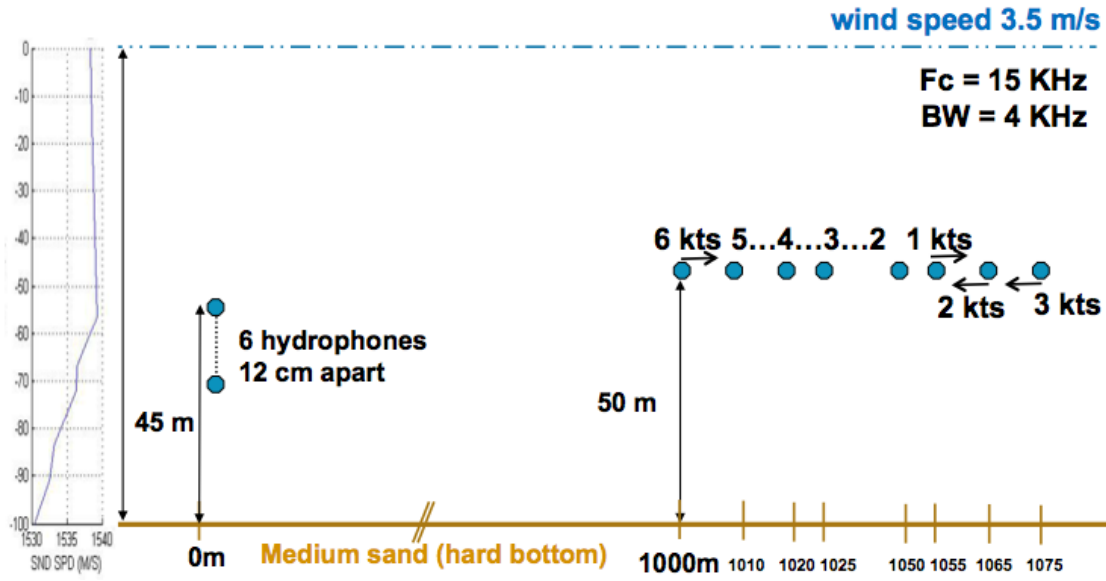
Figure 1: The scenario modeled in the SST simulations.
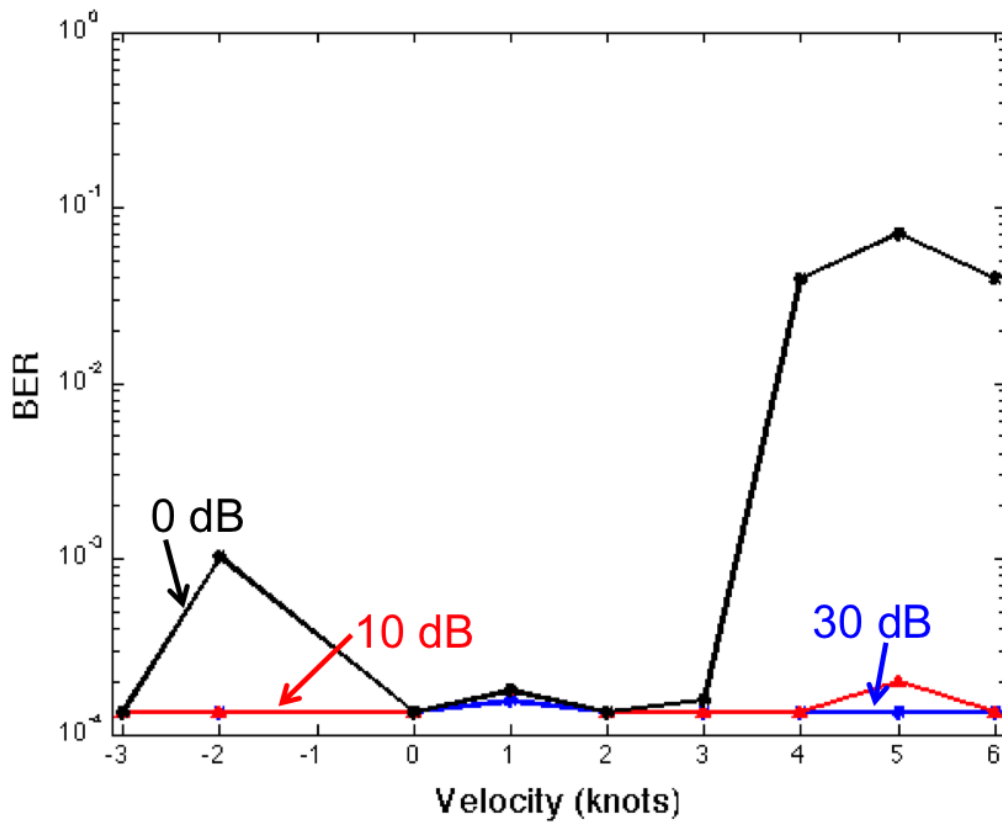

Figure 2: BER averaged over 6 hydrophones for 8 moving sources, in a single-user, single-hydrophone scenario with no ISI and for various SNRs.

phone-averaging strategy works very well, as shown in Figure 4. We notice that the BER from the phone-averaged receptions is pushed back to near zero-error.
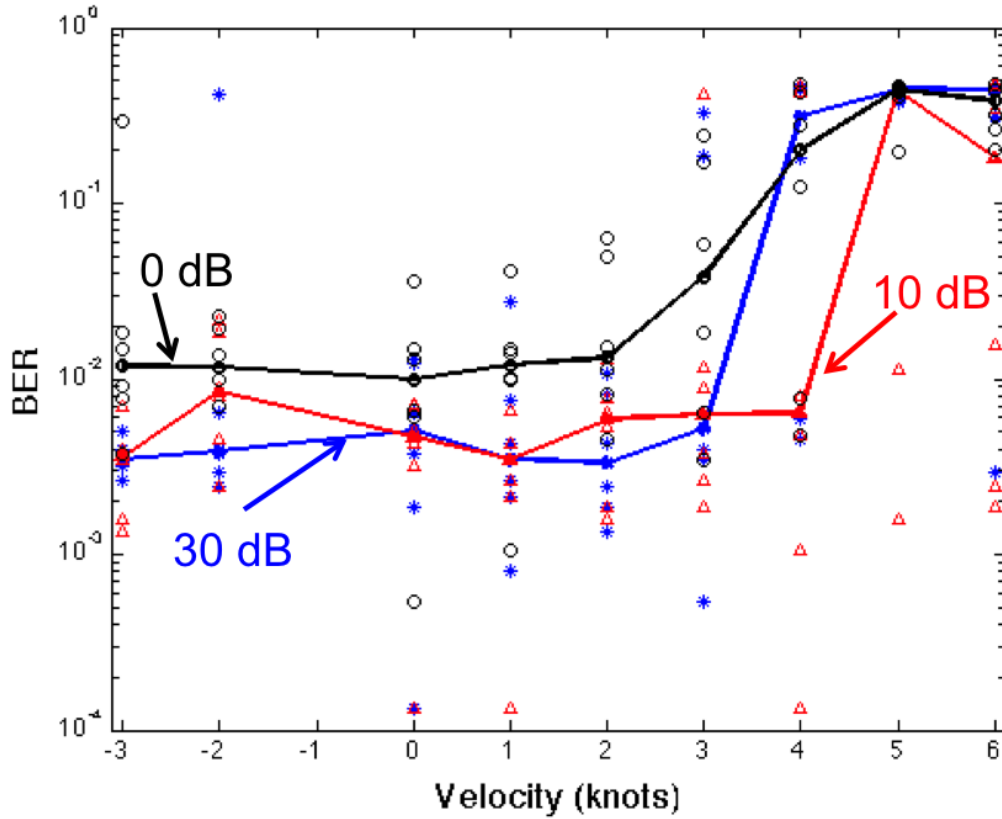

Figure 3: Median BER over 6 hydrophones for 8 moving sources, in a single-user, single -hydrophone scenario with very strong ISI. For each source, the dots indicate the BER for each of the 6 hydrophones in the receiver array; the lines plot the median BER.

Finally, we want to evaluate the performance of DFH in multi-user scenario, that is when multiple users are transmitting at the same time, thereby interfering with each other. For this purpose, we computed the BERs for a variety of combinations of two-user cases, using both single-hyrdophone and hyrdophone averaging, for the case of very strong ISI. Figure 5 shows such results. First, note that single-hyrdophone processing is inadequate for multi-user scenarios. Second, phone averaging helps, but still does not match the performance of the static case, that is it does not overcome the effects of Doppler as well as it did for the single-user case. The reason for this is that the current DFH receiver does not track Doppler. Based on this result, our partner BAE Systems is currently investigating a further improvement to the DFH receiver that would incorporate both delay and Doppler tracking. We hypothesize that this further improvement, comprising full tracking and phone averring, will further improve the BER and push DFH toward a fully automatic mode of operation for tough environments with multiple, moving sources.
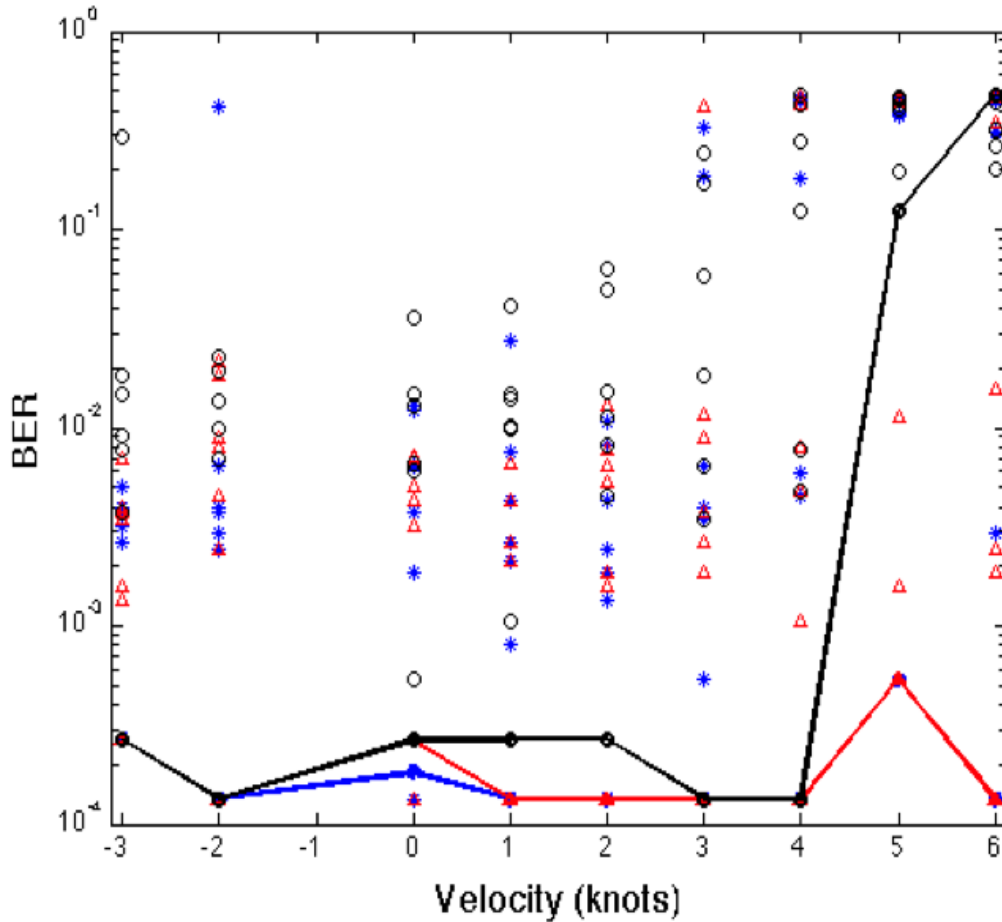
Figure 4: BER for the phone-averaging approach for 8 moving sources, in a single-user scenario with strong ISI. For each source, the dots indicate the BER for each of the 6 hydrophones in the receiver array; the lines plot the BER computed from the waveform averaged across hyrdophones.

IMPACT/APPLICATIONS

The potential applications of DFH are in underwater acoustic communications for asynchronous command and control of unmanned vehicles, where robustness to Doppler and resilience in the presence of multiple users is important.

RELATED PROJECTS

The PI is not currently working on related projects.

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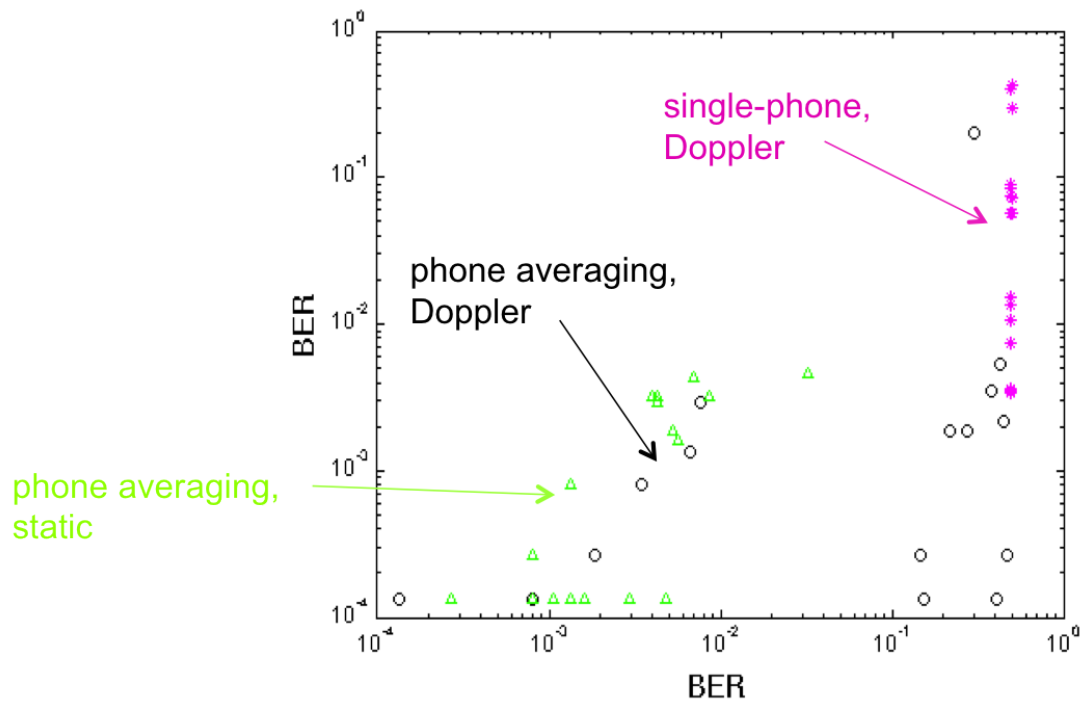
Figure 5: BER for the two-user case. The final goal is to push DFH toward the low BER range.

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PUBLICATIONS

- "Differential Frequency Hopping (DFH) Modulation for Underwater Mobile Ad-Hoc Networks," D. Egnor, G. Edelson, L. Cazzanti, A. Das, USN JUA.